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The Use of Haptic Display Technology in Education

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Abstract

The experience of "virtual reality" can consist of head-tracked and stereoscopic virtual worlds, spatialized sound, haptic feedback, and to a lesser extent olfactory cues. Although virtual reality systems have been proposed for numerous applications, the field of education is one particular application that seems well-suited for virtual reality technology. Recently, in the field of education, virtual reality systems equipped with haptic devices, have been used to assist in the learning process. The main benefit of haptic technology for education is that it increases the realism of simulations by providing force or tactile feedback to the user. Such feedback can be used to model the atomic orbits of electrons, feel of tissue of the abdomen during a laparoscopic training exercise, or visualize and interact with nanoscale materials. This article discusses the basics of the haptic sense, discusses a few common haptic devices, and concludes with current applications of haptics in education.

Introduction

This article discusses the use of haptics in education. The word "Haptics" derives from the Greek *haptein* meaning "to fasten" and generally refers to the sense of touch. In the field of virtual reality, haptics is the science of applying touch sensation and control to interaction with computer applications. The term “Haptics” was first introduced in 1931 and its origins can be traced back to the Greek words *haptikos* meaning *able to touch* and *haptesthai* which translates to *able to lay hold of* (Revesz, 1950). Today the term, in its broadest sense, encompasses the study of touch and the human interaction with the external environment via touch. According to researcher members of the NanoScale Science Education group, the field of haptics is multidisciplinary, and involves research from engineering, robotics, developmental and experimental psychology, cognitive science, computer science, and educational technology. Further, recent technological advances in creating portable and relatively low cost haptic devices, are allowing the sense of touch to be added to a variety of teaching applications throughout the education curriculum. This article first discusses the case for haptics in education, then discusses the basics of the haptic sense, introduces a few common haptic devices, and concludes with a brief discussion of current applications of haptics in education.

The case for haptics

The use of auditory and visual presentation techniques dominates in educational settings. Even in the field of virtual reality, the display of information for educational purposes is primarily vision based, even though the student has other senses that can be used to acquire and process information (Danas & Barfield, 1996). In many subjects, the understanding of how forces act on objects is an important concept, though the ability to directly feel the forces described by algorithms is just beginning to be integrated into science curriculum. Haptic display technology attempts to solve the problem of allowing students to feel the forces acting on objects within virtual reality simulations by presenting force (kinesthetic) or tactile feedback to the user (Barfield & Furness, 1995; Burdea, 1996).

Allowing students to actively touch and explore objects has been shown to aid the process of learning; for example, allowing students to directly manipulate objects may assist the student in overcoming conceptual barriers to difficult science, mathematics, and engineering concepts. Currently, difficult problems in technical fields are most often presented in a passive and abstract manner, neither of which is an effective teaching technique. In contrast, haptic technology leads to active participation and interaction with course material – thus more directly involving a student in the learning process. For these and other reasons discussed as follows, the use of haptic display technology may be particularly beneficial in education.

In education, the use of haptic devices should be particularly beneficial in any situation where it is important for the student to experience a realistic simulation of forces. However, with most current virtual reality displays, if a user tries to touch a virtual object there isn't a non-visual cue to let the user know that the object is in contact with the user's hand. Also, there may not be a mechanism to keep the user's virtual hand from passing through an object viewed using a virtual reality display. Haptic technology can be used to "close-the-loop" between vision and touch. That is, with haptic display technology, the student can touch the surface of a virtual object, feel any forces that may be acting on the object, and feel any forces that the virtual object may exert on other objects displayed in the simulation.

The use of haptic technology should be beneficial for a range of tasks associated with the process of learning. For example, imagine trying to teach a student the task of reaching behind a piece of virtual equipment to repair or replace a part. Without the sense of touch, this task is formidable. In this case, the student's virtual hand will likely pass through the equipment due to a lack of haptic feedback when the hand reaches the surface of the equipment. When teaching a student to repair and maintain equipment, even though the visual channel, as (computer) output, is primary; the tactile and force senses are also important. In fact, tactile feedback has been shown to be effective for many tasks. For example, a simple use of tactile feedback is shape encoding of manual controls, such as those standardized in aircraft controls for landing flaps, landing gear, the throttle, and so forth (Chapanis, 1965). Further, shape encoding is particularly important if the operator's eyes cannot leave a primary focus point or when operators must work in the dark. Not surprisingly, systems with tactile feedback, called *tactile displays*, have been developed as a sensory replacement channel for handicapped users. The most celebrated product is the *Octacon*, developed by Bliss and colleagues (Bliss, Katcher, Rogers, & Sheppard, 1970). This tactile reading aid, which is still in use, consists of 144 piezoelectric bimorph pins in a 24-by-6 matrix. A single finger is positioned on the array (an output device) while the opposite hand maneuvers an optical pickup (an input device) across printed text. The input/output coupling is direct; that is, the tactile display delivers a one-for-one spatial reproduction of the printed characters. Reading speeds vary, but rates over 70 words per minute after 20 hours of practice have been reported (Sorkin, 1987).

There are many courses which should directly benefit from the use of haptic technology. Some of these include: chemistry, molecular biology, statics, dynamics, mechanics, chemistry, and physics. In each of these courses, the understanding of forces is essential to enable mastery of the course material. That is, the underlying concept being taught may be directly tied to the understanding of forces exerted on or between objects; for example, in engineering, knowledge of the forces acting on engineering structures is essential for constructing a wide range of objects such as buildings, roads, and bridges. In addition, the experience of forces may be a secondary component of the lesson, although still essential for learning the course material. For example, in medical training a student is taught to palpate a patient by touching an organ or area of the body. In this case, the diagnosis of a disease is the primary goal, but the ability to feel objects to determine its size, shape, firmness, or location is essential for the diagnosis. On the point of using haptic technology as an aid in learning, a study conducted at the University of North Carolina found that participants were able to more efficiently learn virtual mazes when haptics were added than when there were no haptic feedback cues (Insko, Meehan, Whitton, & Brooks, 2001).

Medical practitioners may also use palpation to feel for tissue texture (for example, swelling or muscle tone), to assess range and quality of joint motion, and to assess tenderness through tissue deformation for example, provoking pain with pressure or stretching) (Hart & Karthigasu, 2007). To teach this skill, haptic technology is currently being used in a number of teaching hospitals to train students to palpate virtual patients. Also, haptics technology is used in telesurgery in which the physician is remote to the patient. That is, using haptic technology physicians are being trained to use remote touch in minimally invasive surgery through the use of haptic interfaces with force sensors that allow the surgeon to "feel" tissues and organs during surgery (Hemal & Menon, 2002; Lederman, 1983).

The use of haptic technology should also be useful for academic disciplines other than the physical and medical sciences. For example, in an introductory life science course, or an even more advanced cell or molecular biology class, haptic technology can allow students to "poke" through cell membranes, "feel" the viscosity of the cell cytoplasm, and "touch" the rough endoplasmic reticulum structure within the cell. Haptic technology can also assist students in learning basic concepts in biology, such as how particular molecules traverse the cell membrane via the various types of passive transport. This can be done by allowing students to move molecules through the cell membrane and then "feel" the associated forces which result from the interactions of different molecules. Other applications of haptic technology in education could include: in the arts, the manipulation of virtual sculptures; in geography, the manipulation of geographic databases viewed as stereoscopic images in virtual reality; in statistics, allowing students to feel the difference in population parameters (such as weight, income level, and so forth) of statistical databases; in geology, allowing students to create models of different kinds of rocks and surfaces and to allow students to feel the difference in hardness, shape, and texture of rocks and minerals; and in anthropology, to allow students to create an ancient virtual dig and to allow students to extract ancient artifacts.

Are there any principles of learning which are supported by the use of haptic technology? A basic tenet of education is to actively involve students in the investigation of the properties of an object. Contrast active participation and manipulation of objects with passive learning, such as watching a science video or reading a text. In passive learning, the student is asked only to sit and observe. In such passive learning situations, it is difficult for the student to maintain attention and motivation compared to when active participation is allowed. This is because in active participation the student expends energy and makes decisions to explore the properties of objects. In addition, in active learning, the student is able to "take control" of the learning process and therefore more directly control the speed of exploration and learning. Finally, another benefit of active participation for learning is that active participation has been shown to be an important part of intrinsic motivation (Deci & Ryan, 1987; Deci, Spiegel, Ryan, Koestner, & Kauffman, 1982), and techniques to improve motivation are especially important in the education of pre-college students.

Another benefit for education that should result from the use of haptic technology is an increase in the "presence" felt while exploring a simulation. Presence can be thought of as the sense of "being there" in a simulation (Barfield & Weghorst, 1993). Presence has several characteristics; for example, presence is related to a feeling of computer transparency, where the interface to a computer fades into the background. As presence or transparency increases, so does the experience of working on a task as opposed to working on a computer. This has long been a goal in developing usable systems and the principle of making interfaces transparent should be relevant for education as well. In addition, from a perspective in rhetoric and argumentation, presence is the quality which makes certain elements important and pertinent to an audience; therefore, to the extent that haptic feedback increases the important aspects of a lesson, presence in the course material should increase, and with that, learning. One historical method to increase presence is to use concrete rather than abstract objects; haptic technology is compatible with this goal, as haptics allows the student to feel virtual objects thus increasing the "concreteness" of the material compromising a lesson.

Considering vision and haptics

Even though vision-based lecture techniques dominate in most education settings, researchers have shown that haptics is superior to vision in assisting learners in detecting properties of texture (roughness/smoothness, hardness/softness, wetness/dryness, stickiness, and slipperiness) as well as microspatial properties of pattern, compliance, elasticity, viscocity, and temperature (Lederman, 1983; Zangaladze, Epstein, Grafton, & Sathian, 1999). When haptics is compared to vision in the perception of objects, vision typically is superior, with a number of important exceptions. Visual perception is rapid and more holistic – allowing the learner to take in a great deal of information at one time. Alternatively, haptics involves sensory exploration over time and space. For example, if you give a student an object to observe and feel, the student can make much more rapid observations than if you only give the student the object to feel without the benefit of sight.

It has also been shown that vision dominates when the goal is the perception of macrogeometry (shape), but haptics is superior in the perception of microgeometry (texture) (Sathian, 2000; Sathian, Zangaladze, Hoffman, & Grafton, 1997; Verry, 1998). In education, exploring the texture of an object may be the primary method for understanding course material. For example, in a textile and fabric class, the texture of the fabric may be essential for a design project. In addition, many of the situations in which haptics may be used in the learning process will not require haptic feedback as the sole learning aid, but haptic feedback will likely be used in combination with a visual display. For example, haptic technology in combination with a visual display is currently being used by some teaching hospitals to train practitioners for tasks which require hand-eye coordination, such as surgical endoscopic and laparoscopic procedures. The benefits of such techniques are that haptics and vision together can be superior to either alone in many learning contexts. However, there are cases where the haptic sense must be utilized as the primary technique in education. For example, students with visual impairments depend on haptics for learning through the use of Braille (Sathian, 2000).

The haptic sense

This section presents a brief overview of the haptic sense, provided only to orient the reader to the material in the article. More comprehensive reviews can be found in Burdea (1996), and Durlach and Mavor (1995). Interestingly, the sense of touch is the only one where the entire system conducts both sensing and actuation. For example, our hands are used both to sense the temperature of a stove, and to move away in case it is hot. Further, touch is one aspect of the important and varied *mechanoreceptive* senses. Touch, the vestibular (or equilibrium) sense, and sound all involve sensitive cells that react to a mechanical stimulus. Deformation of the cell causes a change in electric potentials and the initiation of a nerve impulse. Many of these cells have tactile hairs, such as the hair cells of the semicircular canals and the cochlea. In addition, many touch organs communicate with ganglia in the spinal cord, and may be part of a *reflex arc* that does not involve processing by the brain. Although touch may seem to involve less mental processing than the other senses, large volumes of the brain are associated with parts of the body, and touch may play a large role in learning and memory.

Tactile sensory information from the hand in contact with an object can be divided into two classes: (1) tactile information, referring to the sense of contact with an object, mediated by responses of low-threshold mechanoreceptors innervating the skin with and around the contact region, and (2) kinesthetic information, referring to the sense of position and motion of limbs along with the associated forces conveyed by the sensory receptors in the skin around the joints, tendons, and muscles, together with neural signals derived from motor commands. Further, touch sensors provide information on contact-surface geometry (if on a flat surface or an edge), the smoothness of the contact surface, its temperature, or even a grasped object's slippage due to gravity. Conversely, force feedback gives information on the total contact force, on contact-surface compliance (hard or soft), or grasped object weight (heavy or light). Also, it is known that kinesthetic stimulation maps roughly to forces being exerted on, and sensed by, mechanoreceptors in the joints, tendons, and muscles. For example, we feel the weight of a heavy object held in an upturned palm because the object weight exerts forces on the wrist, elbow, and shoulder joints, and we exert opposite forces to counter the weight. Proprioception, knowing where your limbs are without looking at them, is another example of a kinesthetic sense.

Generally, the process of haptic perception involves sensors in the skin as well as the hand and arm. As noted above, the movement that accompanies hands-on exploration involves different types of mechanoreceptors in the skin (involving deformation, thermoreception, and vibration of the skin), as well as receptors in the muscles, tendons, and joints involved in movement of an object (Verry, 1998). These different receptors contribute to a neural synthesis that interprets position, movement, and mechanical skin inputs. Druyan (1997) argues that this combination of kinesthetics and sensory perception creates particularly strong neural pathways in the brain. For the science learner, kinesthetics allows the individual to explore concepts related to location, range, speed, acceleration, tension, and friction. More generally, haptics enables the learner to identify hardness, density, size, outline, shape, texture, oiliness, wetness, and dampness (involving both temperature and pressure sensations) (Druyan, 1997).

Some haptic devices

Essentially, force display technology works by using mechanical actuators to apply forces to the user. By simulating the physics of the user's virtual world, forces acting on objects can be computed in real time, then sent to the actuators so that the users feel them. Force display is especially useful for communicating surface texture and bulk properties of objects and environments as well as dynamics of objects. Current technologies for generating force-feedback stimuli may be cumbersome, have limited range of motion, and are designed for special purpose applications. On the other hand, these devices can typically generate strong forces and arrest user motion in a realistic manner (Figure 1). In contrast, tactile devices typically generate weaker forces than force-feedback devices. As with sound, a tactile stimulus is made up of a signal with varying frequency and amplitude. Much work with tactile displays has focused on the use of pin arrays for stimulating one of the most sensitive parts of the body, the distal finger pad of the index finger. More recent work has focused on the use of large numbers of inexpensive vibrating DC motors distributed over a larger area of the body. Generally, tactile devices cannot arrest the motion of the user, but can provide a means for displaying contact cues, as well as other types of information.

A standard input device capable of supplying force feedback is The PHANTOM (Massie & Salisbury, 1994). This device allows users to explore application areas that require force feedback in six degrees of freedom. Additionally, the PHANTOM provides torque feedback in three rotational degrees of freedom in the yaw, pitch and roll directions. Some PHANTOM systems provide a range of motion approximating lower arm movement pivoting at the elbow; currently the higher end version of the PHANTOM has a range of motion approximating full arm movement pivoting at the shoulder. As noted, the PHANTOM device can simulate torque, a measure of how much a force acting on an object causes that object to rotate, thus making it possible to feel the collision and reaction forces and torques, for example, in a virtual assembly path, or the rotational torques supported by a remote "slave" robot in a

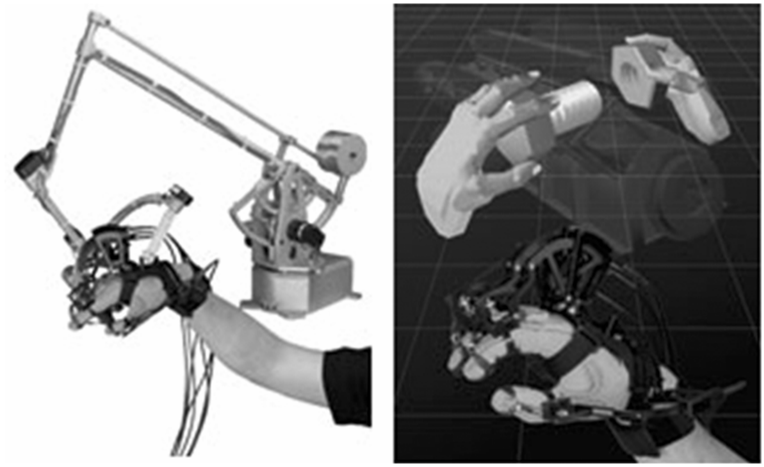

Figure 1. Two examples of a force feedback device, Reproduced by permission of Immersion Corporation, Copyright ©2008 Immersion Corporation, all rights reserved.

teleoperation environment. Application areas where the PHANTOM is being used include virtual assembly, virtual prototyping, maintenance path planning, teleoperation, medical training, and molecular modelling.

Another haptic device is the CyberGrasp system which is a force feedback device designed for the fingers and hand. The device lets a user "reach into a computer" and grasp computer-generated or tele-manipulated objects. Specifically, the CyberGrasp device is a lightweight, force-reflecting exoskeleton that fits over a CyberGlove data glove (wired version) and adds resistive force feedback to each finger. With the CyberGrasp force feedback system, users are able to feel the size and shape of computer-generated 3D objects in a simulated virtual world. Grasp forces are produced by a network of tendons routed to the fingertips via an exoskeleton. There are five actuators, one for each finger, which can be individually programmed to prevent the user's fingers from penetrating or crushing a virtual solid object. The high-bandwidth actuators are located in a small actuator module, which can be placed on the desktop. The CyberGrasp system is used for medical training, virtual reality training and simulation, computer-aided design (CAD), and the remote handling of hazardous materials. In addition, the CyberGrasp system can supply a force of 12 N (Newton) per finger.

In a device designed to provide tactile information (called Sandpaper), Minsky, Ouh-Young, Steele, Brooks, and Behensky (1990) added mechanical actuators to a joystick and programmed them to behave as virtual springs. To create surfaces with different textures, Minsky and colleagues computed the position, velocity, and acceleration of the joystick and the geometry and equations of motion to derive the output forces produced by the joystick. How did the system work? When a cursor was positioned over different grades of virtual sandpaper, the springs pulled the user's hand toward low regions and away from high regions. In an empirical test that was done without visual feedback, users were able to reliably order different grades of sandpaper by granularity thus showing the system was effective at providing tactile information to users. Such a system is relatively low cost and portable, and should be beneficial in any training situation requiring students to distinguish a material based on its texture.

In another haptic device, this one with the capability to provide tactile and force feedback, Akamatsu, Sato, and Hasbroucq (1993) modified a mouse by inserting a solenoid-driven pin under the mouse button to provide tactile feedback and an electromagnet near the base of the mouse to provide force feedback. Tactile stimulus to the finger tip was provided by pulsing a solenoid as the cursor crossed the outline of screen objects. Force feedback to the hand was provided by passing current through the electromagnet to increase friction between the mouse and an iron mouse pad. Friction was high while the cursor was over dark regions of the screen (for example, icons) and was low while the cursor was over light regions (background). In an experiment using a target acquisition task, movement, time and accuracy were shown to improve with the addition of tactile and force feedback compared to a vision-only condition (Akamatsu, MacKenzie, & Hasbroucq, 1995). A similar system was described by Engel, Goosens, and Haalma (1994) using a trackball with corrective force feedback to “guide” the user toward preferred cursor positions. One potential benefit in adding force and tactile feedback for education is that the processing demands of the visual channel is diminished, freeing up capacity for other purposes.

Examples of haptics in education and training

Medical training

In the future, surgeons using haptic technology may work from a central workstation, performing operations in various locations, with machine setup and patient preparation performed by local nursing staff. A particular advantage of this type of technology is that the surgeon will be able to perform many more operations of a similar type, and with less fatigue (Marescaux et al., 2002). However, mastery of the skills necessary to perform telesurgery, will require extensive training with simulators that provide haptic feedback.

Various haptic interfaces for medical simulation have been designed for training of surgical procedures such as minimally invasive surgery (laparoscopy/interventional radiology) and remote surgery using teleoperators (Faber & von Wowern, 2004).

Such technology has several benefits for training. For example, using haptic devices for surgical training, if a surgical instrument contacts virtual tissue, the surgeon will feel the characteristics of the tissue, thus, improving the reality of the training exercise. As another way to increase simulator realism, some haptics technology has been designed to give physicians force feedback in their hands which mimics how tissue and blood vessels feel and behave in real life.

What are some other benefits of haptics for training medical procedures? From an education perspective, it is well documented that a surgeon who performs more procedures of a given kind will have statistically better outcomes for his patients; this is, of course, the most important benefit of virtual reality training in medicine. Also of interest to education is the issue of transfer of training from a virtual reality simulator equipped with haptics to the real world. The goal of training using a simulator is to teach skills which, once learned in a virtual environment, transfer to the real world. On this point, in a study by Seymour and colleagues at Yale University (Seymour et al., 2002), a group of surgical residents performed a laparoscopic cholecystectomy procedure (that is, a surgery to open the abdomen to remove the gallbladder) with or without exposure to a virtual reality training simulator that included a laproscopic interface input device. A study comparing performance between experimental (access to virtual reality training) and control groups found that the surgical residents trained using the simulator were 29% faster performing a gallbladder dissection and less likely to injure the gallbladder or burn non-target tissue than the control group which was trained using standard procedures. One conclusion made by the research team, of relevance for education and training, was that use of the laparoscopic system was successful in transferring skills acquired with the simulator to a real-world operating room environment.

Researchers at the MedICLab (Medical Image Computing Laboratory), Universidad Politécnica de Valencia, Spain (Meier et al., n.d.) have also explored the use of a haptics based simulator for training surgical procedures. Their training focuses mainly on minimally invasive surgery, which is a technique that permits interventions through very small incisions (Monserrat, 1999; Monserrat, Meier, Alcañiz, Chinesta, & Juan, 2001). Minimally invasive surgery reduces the patient's trauma and permits a faster recovery in comparison with classical surgery. The disadvantage of this surgery technique, though, is its complexity, requiring a high training effort for the surgeon. To alleviate this problem, researchers at MedICLab developed a general surgery simulator with the capability to provide haptic feedback. The virtual environments used in the training simulations are composed of synthetically generated organs with arbitrary pathologies. As stated, the surgical intervention is carried out by means of a haptic interface, providing the surgeon with a sense of touch, a fundamental element of all types of surgery.

Chemistry

The use of haptics technology in chemistry can be beneficial in the curriculum of several courses. For example, in introductory chemistry classes, haptic technology can be used to model the forces generated by chemical bonds, thus allowing the student to "feel" the spatial structure of molecules. In more advanced courses, haptics technology can be used to assist researchers and graduate students in designing and visualizing complex molecular structures, predicting native protein conformations, and understanding the binding interactions of macromolecules; note that the latter two problems dominate the field of computational chemistry (Ouh-Young, Pique, Hughes, Srinivisan, & Brooks, 1988).

Haptics technology in chemistry can also be used to aid researchers in an investigation of protein ligand interactions – where a ligand is a molecular group that binds to another chemical entity to form a large complex. Protein-ligand interactions in biochemical applications determine phenomena ranging from sensory perception to enzyme catalysis. The approach taken by researchers at the University of North Carolina to explore these phenomena is to first develop computationally fast models for simulating molecular interactions and then to use a haptic device during the simulations to guide a ligand into a receptor site while reflecting the forces acting on the ligand to the user in real-time (Ouh-Young, Beard, & Brooks, 1989; Ouh-Young et al., 1988). The benefit from using haptic technology for this type of problem is that use of haptics accelerates the binding process and reduces the development time involved in scientific analysis.

Another use for haptics devices in chemistry is in visualizing the atomic orbits of electrons. Three-dimensional functions that represent atomic orbitals are traditionally difficult for first year chemistry students to conceptualize (Harvey & Gingold, 2000). For this reason, large sections of undergraduate chemistry texts are devoted to breaking apart and simplifying electron density functions so they can be visually represented. Traditional methodologies for this task include three-dimensional projections (color, contours, slices) and two-dimensional graphs. Preliminary work with haptics in this area suggests that the PHANTOM haptic interface providing force feedback is an important addition to the chemist's tool set for representing atomic orbitals. With the PHANTOM, users can move through real three-dimensional space and perceive the electron density as the force on the PHANTOM's pen. In Harvey and Gingolds' system, the force is proportional to the probability density function for the electron at any point, given by the square of the wave-function describing a particular atomic orbital. Nodes are felt as regions of zero force, increasing values are felt as increasing resistance, and maxima are communicated by haptic "clicks". To summarize, haptics technology, such as that used by Harvey and Gingold, and Brooks and colleagues, undertakes the problem of allowing students to "haptically visualize" the properties of individual atoms and more complex molecular structures, thus assisting students in overcoming common conceptual barriers often confronted in first year chemistry classes.

Manipulating molecules

At the University of North Carolina, scientists have combined virtual reality technology with an atomic force microscope to create a nanoManipulator (Carey, 1996; Robinett et al., 1992; Taylor et al., 1993). The nanoManipulator is designed to provide a three-dimensional user interface to scanning probe microscopes such as scanning tunneling microscopes (STM) and atomic force microscopes (AFM). An STM probes by tunneling electrons to and from a sample, while the AFM measures forces between the surface and the tip of a probe. Tunneling is the quantum mechanical phenomenon that describes the ability of lower energy subatomic particles to penetrate higher energy barriers. Specifically, an STM measures subatomic distances by maintaining a constant height and recording current flows between the flow and the sample based on quantum mechanical tunneling effects. An AFM measures atomic forces between a sharp probe and the sample surface to provide an image of atomic and molecular features of the sample. Scanning-probe microscopes allow the investigation and manipulation of surfaces down to the atomic scale. Further, the nanoManipulator couples the microscope to a virtual reality interface that gives the scientist virtual telepresence on the surface of a particular structure, scaled by a factor of about a million to one. The system provides new ways of interacting with materials and objects at the nanometer scale, placing the scientist *on* the surface, *in* control, *while* an experiment is happening.

The nanoManipulator uses virtual reality goggles and a force feedback probe as an interface to provide researchers with a unique way to interact with the atomic world (Figure 2) (Simon, 2001). Using the system, researchers can travel over genes, tickle viruses, push bacteria around, and tap on molecules. Further, the force feedback provided by the system allows researchers to roll structures such as nanotubes, feel the bumps on the crystal surface of a nanostructure, or feel the resilience of a virus molecule. By manipulating molecules with a haptic device, researchers gain greater insight into molecular properties, such as strength, flexibility, durability, and even shape; thus, the nanoManipulator is an important teaching tool in molecular biology and nanoengineering.

Looking at molecules at the nano scale is, in itself, a spectacular teaching aid, but interacting with molecules and moving components—atoms and molecules—is a completely new experience to science education that the nanoManipulator affords. The nanoManipulator allows new discoveries to be made, because both the visual and the haptic sense are stimulated (Robinett et al., 1992; Taylor et al., 1993). For example, according to scientists, when crushed, a virus behaves like a Nerf ball, it deforms and then recovers; experiencing these properties of a virus would be impossible without

Figure 2. The nanoManipulator. A haptic interface with a large-screen graphic display, picture courtesy of University of North Carolina Computer Science Department.

the nanoManipulator (Simon, 2001). The nanoManipulator will also allow researchers to see *and* to feel the results of their theories and models. With this technology, scientists will be able to stretch, twist, push, pull, and, in general, play with their molecules. Most importantly, the nanoManipulator will let chemists, physicists, and biologists run low-level, hands-on, what-if experiments with molecules of interest. In addition to seeing the shapes and flexibility of complex proteins, researchers can explore the different degrees of molecular and atomic attraction of real molecules, then compare the predictions of models with the results in their “bare hands”.

In a recent study (Jones, Andre, Superfine & Taylor, 2003) designed to explore the use of the nanoManipulator for education, students were able to feel nanosized materials such as viruses imaged under the AFM. In essence, the user was afforded the opportunity to have a “hands-on” experience with objects at the nanometer scale that are too small to be touched or even seen otherwise. Specifically, Jones and colleagues examined how tactile and kinesthetic feedback influenced students' learning about virus structure and function. The research conducted with middle and high school students showed that students found the experience highly engaging and developed more positive attitudes about science. Most importantly, students revealed significant gains in their understanding of viruses, particularly virus morphology and diversity of types. Jones and colleagues concluded that the addition of haptic feedback provided a more immersive learning environment that not only made the instruction more engaging, but may have also influenced the way in which the students constructed their understandings about viruses, as evidenced by an increase in their use of spontaneously generated analogies.

Physics and engineering

Many fundamental concepts in physics are so unique that they require the construction of mental models that describe the physical and mathematical relationships of systems. It has been shown that human spatial ability is an important component of human cognition and learning (Bertoline, 1998). Recent research conducted by Ernst and Banks (2002) has shown that the human nervous system combines both visual and haptic information in a statistically optimal fashion. This suggests that inherently dual-modal stimuli, such as that shown in a variety of physics and engineering problems (for example, spring force, electro-static force, gravitation, and so forth) may be better understood when both modalities (vision, haptics) are involved in learning the relationships of the physics phenomena. Therefore, vision-based presentation techniques, when combined with haptic feedback, may be an effective combination in teaching engineering and physics concepts.

In educational settings, especially in subjects where students are required to understand how forces affect system behavior, force feedback displays may be especially effective in helping students understand basic established physical relationships. For example, in the study of kinetics, Newton's second law $F = ma$, where F is the resulting external force acting on the particle of mass m, and a is the absolute acceleration of the particle, a force feedback input devise may be used to allow the learner to "feel" this fundamental law. Once gaining a basic understanding of Newton's second law, the student is better prepared to learn more advanced concepts in physics and engineering that build upon Newton's second law. To illustrate how a haptic device could assist a student in understanding basic laws of nature as presented in a standard first year physics course, consider the following problem.

A block of mass m_1*=2.0kg* on a frictionless inclined plane of angle *20 deg* is connected by a rope over a pulley to another block of mass m_2*=1.0kg*. What are the magnitude and direction of the acceleration of the second block? The figure below which represents a standard teaching aid in physics and engineering will help to visualize the problem.

The force m_1g, caused by gravity, can be decomposed into two forces: F_{1a} and F_{1b}.

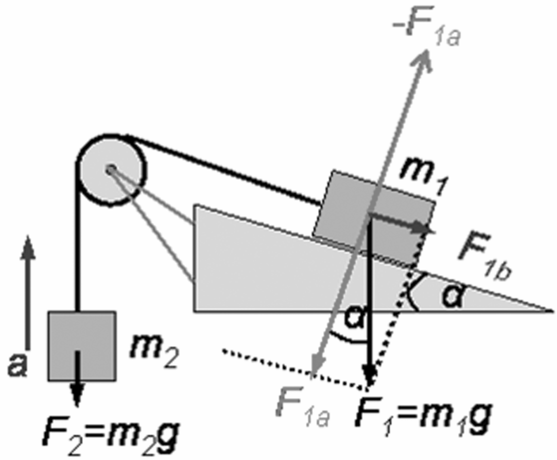

Figure 3. Block diagram for a physics problem emphasizing Newton's laws. The use of haptic display technology will allow the student to change parameters of the problem and feel how the resulting forces change.

Elementary geometry and the definitions of trigonometric functions can be used to write the following:

$$F_{1a} = m_1 g \cos\alpha \tag{1}$$

$$F_{1b} = m_1 g \sin\alpha \tag{2}$$

$$F_2 = m_2 g \tag{3}$$

The force F_{1a}, represented by the F_{1a} vector is compensated, according to Newton's Third Law of Motion, by a force represented by the $-F_{1a}$ vector. So we are left with forces F_{1b} and F_2 acting one against the other through a rope connecting blocks. Given the mass of the blocks, it is reasonable to assume that $F_{1b} > F_2$. This means that block m_2 will move with acceleration a directed upwards.

The resultant force exerted on the blocks is:

$$F_{1b} - F_2 = a(m_1 + m_2) \tag{4}$$

Substituting (2) and (3) into (4), after a little elementary algebra we get

$$A = g(m_1 \sin\alpha - m_2)/(m_1 + m_2) \tag{5}$$

Substituting numbers given in the problem we get

$$a = -1.03 \text{ m/s}^2$$

The minus sign tells us that acceleration has direction opposite to the one chosen for writing the equations leading to the solution of the problem. Some students when presented with a problem like the above, experience a “conceptual block” in understanding how to “visualize” the forces and acceleration described in the problem. Use of the diagram shown in Figure 3 is beneficial to understanding the problem, up to a point. While the basic parameters of the problem are shown in the block diagram, the diagram is not interactive, any forces shown in the diagram cannot be experienced, nor can the parameters of the problem be changed in real time, with corresponding changes in forces experienced by the student. A force feedback device will allow the student to change several parameters of the above problem and then actively feel how the forces described by Newton's laws are affected. By changing the parameters of a problem and immediately feeling the different forces, students will be able to test hypothesis, perform experiments, and use the haptic sense to visualize formerly abstract concepts.

Schools are under increasing pressure to place disabled students in science and engineering curricula and to provide such students an educational experience within the least restrictive environment. Unfortunately, this requirement presents a challenge with respect to the science classroom, because teaching science involves hands-on experiments that are often difficult to modify for disabled students. To address this challenge, there are several haptic devices which can be used to assist disabled students in understanding material presented in science courses. For example, the Logitech Wingman Force Feedback Mouse is a commercially available device commonly used in video games to provide realistic user interactions with computer generated characters and environments; such a device can also be used to provide haptic feedback to disabled students.

To test the feasibility of using the Logitech for blind and normal sighted students, a usability study was performed that included a legally blind mechanical engineering student (Erlandson, n.d.). The study involved simulating three variables, the relationship between a spring’s length, applied force, and spring constant. One part of the usability data was the students’ verbal expression of the usability of the haptic technology. Results of the usability analysis showed that the computer simulation performed to determine the force constant of a spring by using a force-feedback mouse was very effective for the disabled user. Further, the students (blind, and normal sighted) indicated that the feel of the spring being compressed added a reality to the simulation that went far beyond simply crunching numbers in standard computer simulations. Thus, as this verbal protocols demonstrated, the Force Feedback Mouse used to understand basic concepts in physics improved the quality of the educational experience for both the visually impaired and fully sighted students.

Concluding remarks

Educators are continually challenged to provide physical examples to students in order to make course material more interesting and accessible. Standard teaching methods such as laboratory exercises, software simulations, and in-class demonstrations are all helpful in developing students' ability to connect theoretical principles with physical reality. However, even with these aids, concepts such as eigenvalues, instability, and time constants are often mysterious when students cannot feel their effects. To provide an intuitive connection between the physical world and mathematical concepts, haptic technology is currently being integrated into course curricula. The benefits of haptics technology for education are clear when one considers the remarkable capabilities of the human hand. That is, the human hand is a versatile system that is able to press, grasp, squeeze, and stroke objects. Further, the human hand can be used to explore object properties such as surface texture, shape, and softness, and it can be used to manipulate tools for repairing equipment or to perform delicate surgery. Being able to touch, feel, and manipulate objects in an environment, in addition to seeing (and hearing) them, provides a sense of immersion in the environment that is otherwise not possible.

Based on advances in the design of virtual reality technology, computer simulation and haptic technology have together added a whole new dimension to science education. Today we are observing an increased departure from the traditional method of teaching to an adoption of computer-assisted teaching methods. Commentators have argued that the key to a student's success in science and engineering is to develop an intuitive understanding of the physical systems involved. In the traditional teaching approach, the students frequently learn concepts in a linear fashion and often do not understand the mechanisms involved in the process or where theory merges with the practical application. The incorporation of haptic devices in computer simulation environments provides an excellent method for stimulating both engagement and comprehension in pre-college students that are not audio-visual learners. An interactive audio-visual environment, that is, the traditional method of schooling, can prove to be inefficient and sometimes ineffective for those who learn best by using touch. By addressing this sense of touch, haptic interfaces provide an important tool for helping students who learn best by touch. Haptic technology is also an excellent tool for training, and in assisting scientists in exploring structures from the nano world, to the macro world of everyday life. It is expected that in the future, advances in haptics technology will lead to more portable, high bandwidth, and low-cost simulators to aid educators at all levels of learning.

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